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Fusion Fuel Target Fabrication System Study

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1. EXECUTIVE SUMMARY

The fuel for inertial fusion reactors are complex engineered items which must be made cheaply and in large quantities to continually feed a fusion electrical plant. While this represents a large technical challenge it is ultimately likely doable. The fusion fuel target must be made using different materials and processes than are currently used. Process choices are largely limited by the choice of materials. The selected processes must not only be compatible with the chosen materials but must also satisfy the larger system requirements of producing high-precision, low-cost components in large quantities and be implementable within the time frame consistent with the development of the plant. The system engineering tasks here suggest the options for these materials and processes.

2. MISSION DESCRIPTION

Large amounts of sustainable energy will soon be needed if the current technology-based civilization is to persist in the long-term. An orderly socio-economic transition to a sustainable culture requires the availability and adoption of new technologies that can miraculously replace the incredibly cheap and abundant energy offered by traditional carbon-based sources. Fusion energy is potentially one such technology. In the fusion reaction, hydrogen isotopes deuterium, harvested from water, and tritium, a by-product of nuclear reactions, are fused together to produce helium and high-energy neutrons, the energy of which can be captured to produce electricity. The technological challenges which must be solved to realize this promise are substantial but not out the realm of achievability. One of the many technology issues which must be solved is the availability of cheap fusion fuel targets. Unlike most energy fuel, the fusion fuel targets are highly complex engineered items (See Figure 1). During the fusion reaction, lasers enter the fusion fuel target through the laser entrance hole (LEH) window on the axial ends of the target as shown in Figure 2. They interact with the high atomic weight of the inner surface of the hohlraum wall. Here the laser light is converted to x-rays which bath the capsule surface with intense x-ray energy. This energy ablates the hollow capsule material which shoots outward. The reaction force compresses the DT layer on the inside surface of the hollow capsule to initiate the fusion reaction.

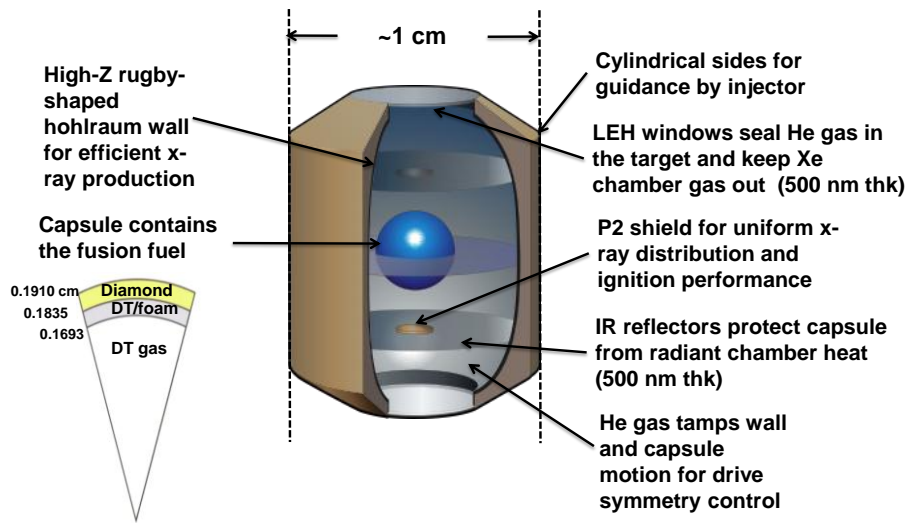


Figure 1. Fusion fuel target

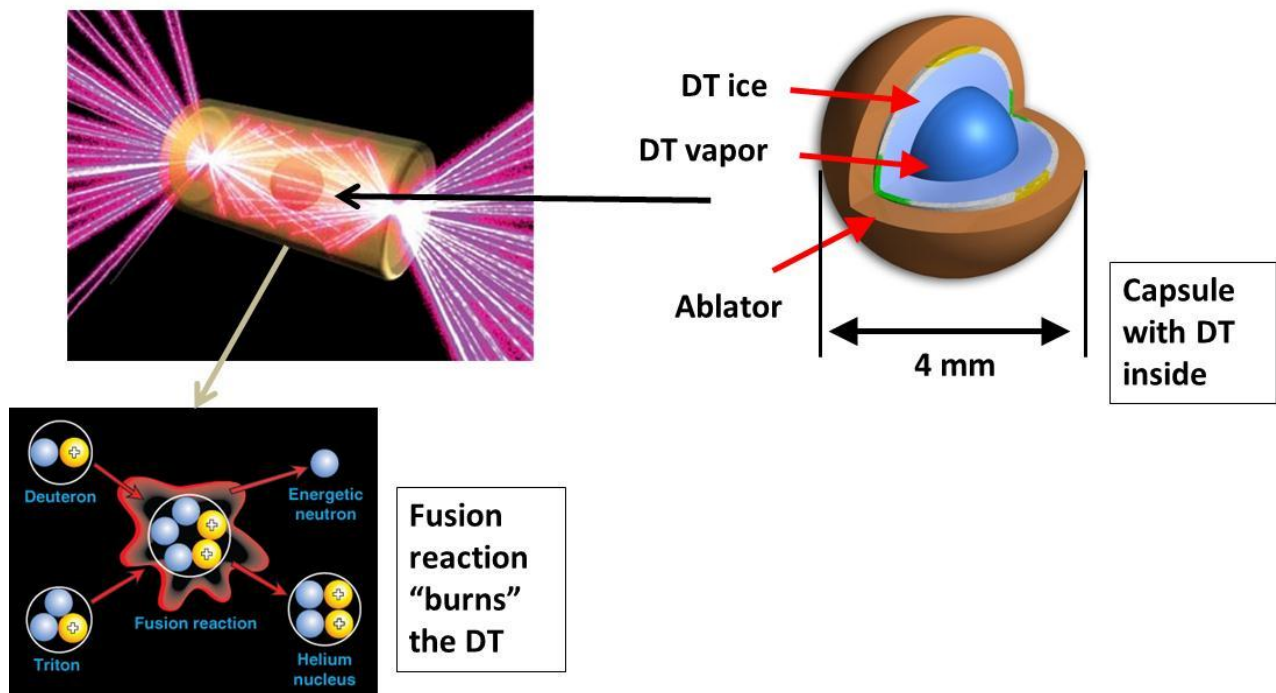


Figure 2. Fusion process

Several manufacturing steps are required to produce these pellets which must be made in quantities of about 1 million per day and less than 50 cents each to compete economically with other energy sources. This study aims to present the system issues associated with the operations for target fabrication.

Basic Fusion Fuel Target Fabrication Process

The nominal fusion fuel target fabrication process is depicted in Figure 3. The capsules are the core of the fusion fuel target. This is where the DT fuel resides on the inside surface of the hollow spherical capsule. The hollow capsules are comprised of a chemical vapor deposited (CVD) diamond layer which is grown on a silicon mandrel. After coating, a hole is laser-drilled through the CVD diamond layer and the silicon mandrel is chemically etched out in a HF-HNO_3 etch-bath. A foam layer is applied to the inside surface of the hollow spherical capsule. The sponge-like foam layer is used to shape the DT layer when the DT is cooled to a liquid or solid state. The capsule is filled with a high-pressure DT gas mixture and the laser-drilled hole filled to seal the DT gas inside the capsule. The capsule is now ready for assembly within the hohlraum sub-assemblies.

In a separate operation, the hohlraum quarters are molded and prepared for assembly. Ultra-thin sheets of polyimide are prepared using a meniscus coating technique. The sheets are glued to the hohlraum. One thin sheet is glued to the outer hohlraum quarter and is used as the laser entrance hole (LEH) window. A second sheet is glued between the hohlraum quarters. The sheet is referred to as the IR shield because it is metalized with a thin 30 nm thick coating to reflect infrared radiation. It also supports a thin high-Z stamped material (lead) disk referred to as a P2 shield. The P2 shield will contain the x-rays and prevent significant ion exit out the LEH window during implosion. A third sheet is used to support the capsule in the hohlraum. This third sheet can be a carbon-nanotube-epoxy layer molded to conform to the capsule shape. The sub-assemblies consisting of the hohlraum quarters are assembled into hohlraum halves. The capsule is placed between the two hohlraum halves to make the final target assembly. The target is cooled ready for launch into the fusion chamber.

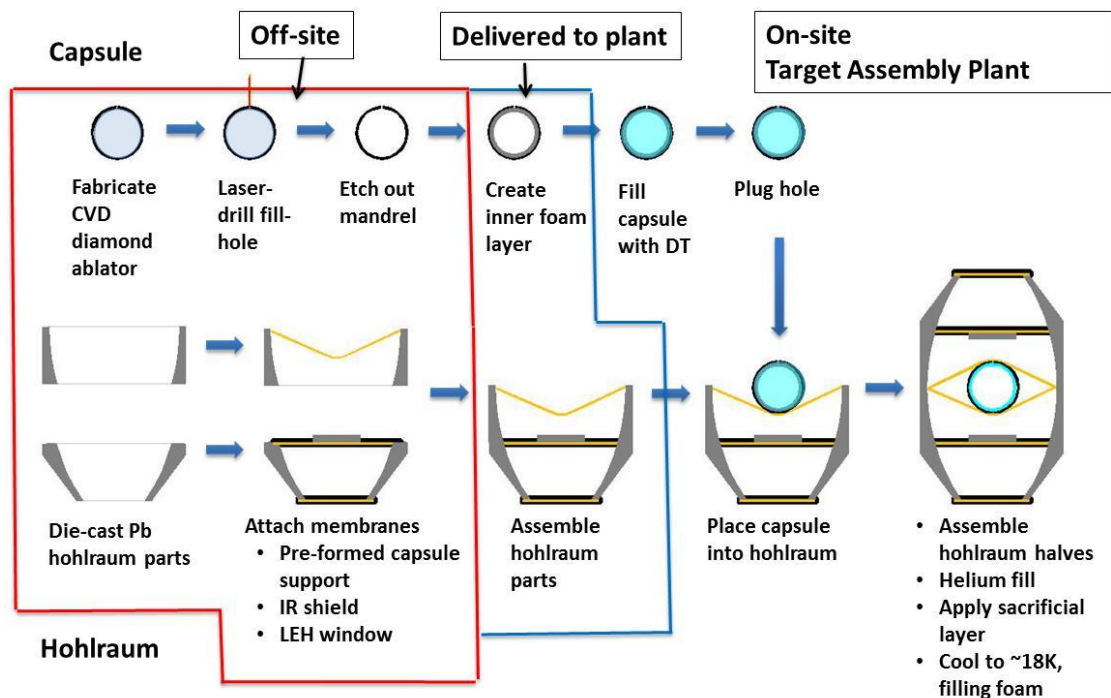


Figure 3. Nominal fusion target fuel fabrication process

2.1 Active Stakeholders

For a fusion fuel target, the active stakeholders include:

1. The factory personnel who must maintain the equipment used to make the target and ensure that the flow of material into and out of the plant is acceptable.
2. The target factory equipment automatically performing the target manufacturing process.
3. The waste disposal personnel who recycle materials and dispose of activated target waste.
4. The safety officers who address concerns about the tritium inventory and activated target waste.

2.2 Passive Stakeholders

The passive stakeholders include:

1. The power company operating the plant which must run smoothly and cheaply to provide the customers with cost-effective electricity on-demand.
2. The physics designer who specify the desired geometry of the target, the allowable tolerances, the composition and the maximum impurity levels.
3. The plant system designer who specifies the gain and yield required for economical plant operation. The physics designer designs the target to meet those requirements.
4. The process engineers/scientist who develop a processes to make the target components.
5. The manufacturing engineer who designs the equipment to meet the process specifications.
6. The fusion chamber designers who must collect the material post-shot for recycling and disposal.
7. The tritium handing system which provides the tritium for use in the target and separates the chamber gas components to recycle the unused tritium and deuterium.
8. The target injection system that injects the target into the chamber
9. The target tracking system which tracks the target flight into the chamber so that the target can be hit by the lasers with high precision.
10. The laser system which interacts with the target to produce the fusion reaction.

3. SYSTEM OPERATION CONTEXT AND REFERENCE OPERATIONAL ARCHITECTURE

3.1 System Operational Context

The operation context diagram for the fusion fuel target fabrication process is shown in Figure 4. The target fabrication process system is represented by the center bubble. Inputs and outputs to the system are indicated by arrows. As described, the fusion fuel targets are built in the fuel factory largely starting from raw materials. The raw materials include lead, methane gas, hydrogen gas, polyimide resin,

aluminum, deuterium and tritium. Various process chemicals are also required such as CO₂ for supercritical drying of the foam layer and HF for the silicon etch-bath solution. A few parts made elsewhere are purchased such as the silicon mandrels for the capsule growth. Machine tools are required such as molds and stamping tooling. Spare equipment parts are needed. Power is required to operate the factory. Design specifications including material specifications, nominal dimensions and tolerances are included. Constraints from other sub-systems such as material composition, production throughput and costs are also inputs. Additional constraints include alignment of the time and schedule for the process development with the cost and schedule of the overall plant development. The outputs are the completed fusion fuel target and waste.

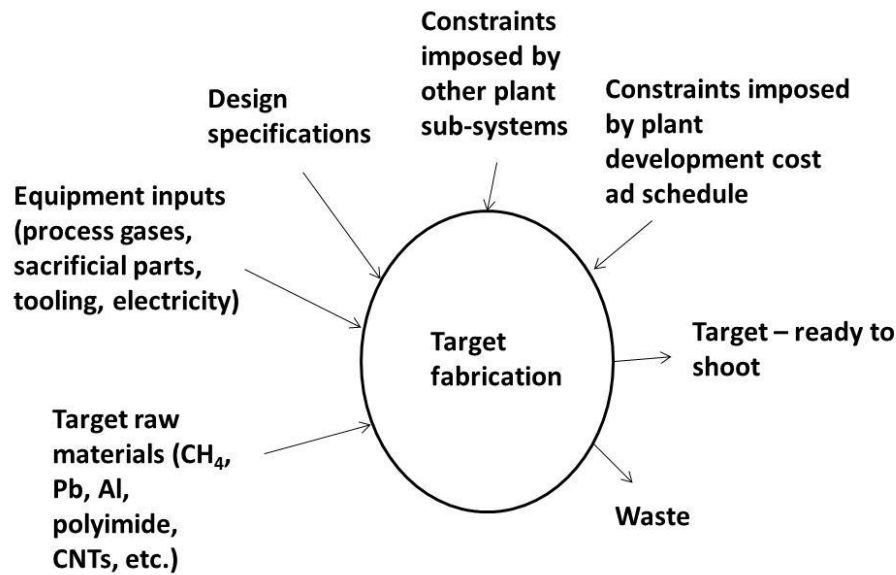


Figure 4. Operation context for fusion fuel target fabrication

3.2 Reference Operational Architecture

The functional architecture for the fusion fuel target factory is shown in Figure 5. The architecture follows the diagram of Figures 3 and 4. Various components such as the capsule, hohlraum and membranes are fabricated and assembled in to sub and final assemblies. Once the final assembly is complete, the target is sent towards the injector where it is filled with helium, the sacrificial layer on the LEH window is applied and the DT layer cooled to a liquid or solid state just prior to injection into the fusion chamber. Once smashed to smithereens in the fusion chamber, the target residue along with any out-of-compliance targets from the factory are sent to various recovery and recycling operations.

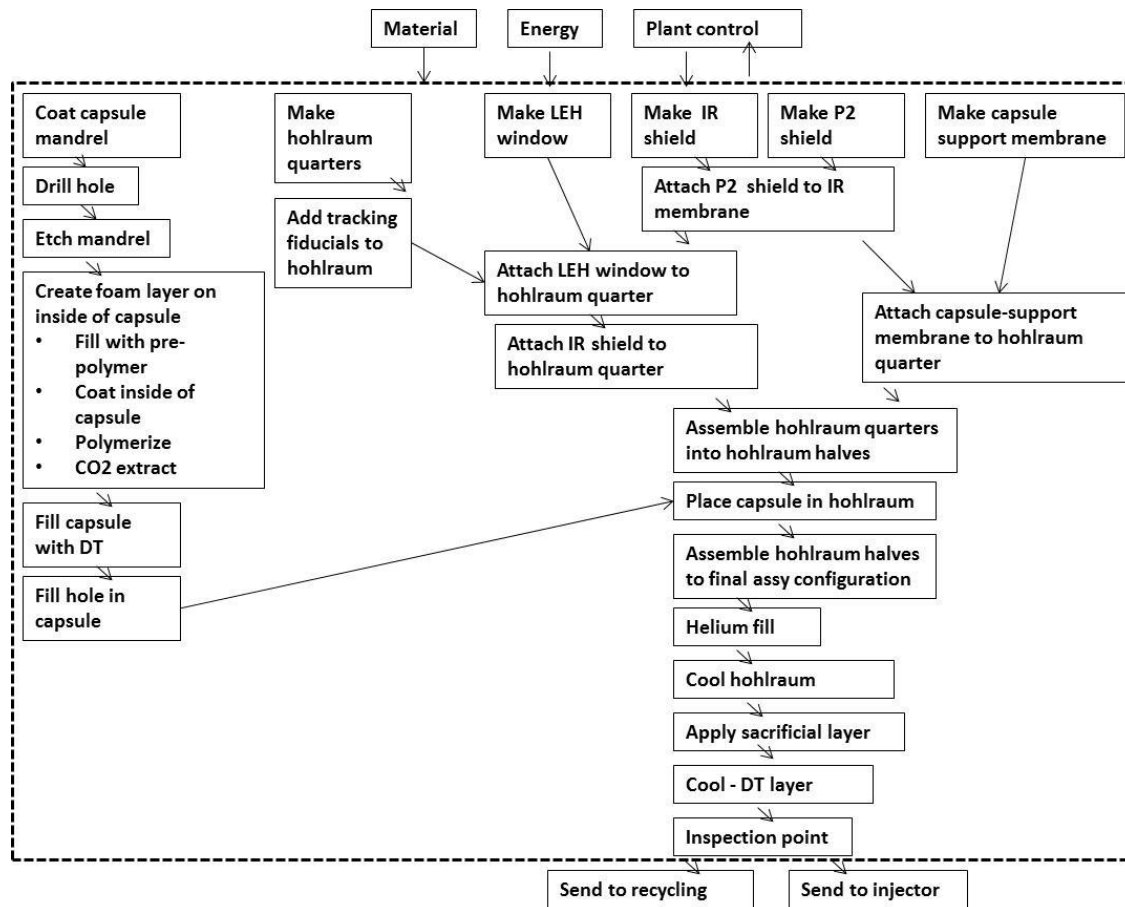


Figure 5. Functional architecture for the fusion fuel target factory

While the overall set of components to be fabricated and the associated assembly processes are relatively stable, the set of material used to fabricate each component and the associated fabrication technique are not well defined. It is these two factors, the materials, and fabrication processes which constitute the major system engineering design issues to be resolved. The baseline system is provided in Table 1. For each fusion fuel component, the point design material is listed and the preferred fabrication technique. The selected fabrication technique is, of course, highly dependent on the chosen material. The material selection is still not finalized for some components, such as the hohlraum and there is still a great deal of flexibility in the choice of fabrication technique.

Table 1. Baseline fusion fuel target fabrication system

Component	Material	Sub operations	Process
Capsule			
Mandrel	Silicon		Etch
CVD diamond coating			Microwave plasma
Foam	DCPD	Dispense	Vacuum fill
		Spin coat	Single axis spinner
		Polymerize	
		CO2 extraction	
Hohlraum	Lead		Press
Tracking fiducials	Reflective ink		Paint (stamp)
Joining material	Polymer adhesives		Paint (Stamp)
Membranes			
LEH window	Polyimide		Meniscus coater
Sacrificial layer	Methane - deuterated		Droplet dispense
IR shield	Polyimide		Meniscus coater
IR reflector	Aluminum		Sputter coat
P2 shield	Lead		Stamp
Capsule support membrane	CNT-epoxy		TBD
Assembly	Polymer adhesive		Fixed tooling

4. SYSTEM DRIVERS AND CONSTRAINTS

The main system drivers are cost, throughput and compliance with strict material and dimensional tolerances. Low costs are required for the system to be competitive with other forms of energy production. Throughput must be sufficiently high to keep the plant operating round-the-clock. And the tight tolerances on the products help ensure optimal operation of the plant. Constraints on the target design are imposed by the fusion physics and the subsystems which must process the pre- and post-implosion target and material. For example, collection of the target debris post-fusion shot and processing of the unused deuterium and tritium impose significant constraints on the target design which in turn impose constraints on the manufacturing processes in terms of which processes can be used to manufacture a component of a given material composition. The requirements and constraints for the system are listed in Table 2. The final column indicates whether or not there is room to negotiate the proposed limits for the requirement in the overall system design.

Table 2. Requirements and constraints for the fusion fuel target components

Parameter	Stakeholder (s)	Requirement	Constraint	Specification
Plant Requirements	Plant operators, customers			
Production quantity		Cost and quantity must be consistent with achieving the cost-of-electricity objectives.		Target production volume shall be 1.3 million targets per day
Target cost				Target cost shall be < \$.50 each
Target physical form		Physical configuration must be consistent with achieving the required gain to meet the plant COE objectives	The physical structure (materials and dimensions) will be defined to meet the gain requirements and will meet the constraints imposed by other plant sub-systems	The dimensions, tolerances and material selection shall be consistent with meeting an average target gain > 60
Development cost and schedule		The process development time/cost must be consistent with the time/cost allotted per the plant development		Processes shall be selected which can satisfy the overall plant cost and schedule requirements
Hohlraum fab	Plant operators, target fab operators, process engineers/scientists, target design			
Production quantity				see plant reqs
Operation cost (COO)		Must meet cost objective for this operation - this cost includes labor, equipment cost, maintenance, consumables, utilities, factory overhead, inspection etc.		Total hohlraum cost shall be < \$0.01 each
Dimensional tolerances				Hohlraums shall be manufactured per dwg
Material selection			<p>Material selection must meet constraints imposed by other plant subsystems. These include:</p> <ul style="list-style-type: none"> - High-Z material on inside surface of hohlraum to sufficient thickness (~25 um) to convert laser light to x-ray energy - Strong enough to survive manufacturing and injection mechanical forces - Thermal isolation from plant environment to keep capsule cool - Tracking fiducials compatible with tracking detection - Compatible with fusion chamber wall - Compatible with laser final optics (Mitigate damage, coating) - Compatible with hydrogen isotope separation (minimal H, no halides to corrupt Pd filters, minimal tritium gettering) - Minor activation to reduce high-level waste - Cost-effective recyclability 	

Membrane fabrication					
Production quantity				see plant reqs	No
Operation cost (COO)		Must meet cost objective for this operation - this cost includes labor, equipment cost, maintenance, consumables, utilities, factory overhead, inspection etc.		Total per membrane cost shall be < \$0.01 each	Yes
Dimensional tolerances				Membranes shall be manufactured per dwg	Yes
Material selection			<p>Material selection must meet constraints imposed by other plant subsystems. These include:</p> <ul style="list-style-type: none"> - Low-Z material to avoid interference with x-rays - Thin to be destroyed by laser light - Strong enough to survive manufacturing and injection mechanical forces - LEH window prevents chamber gases from entering target and He in target from getting out - LEH window may support thermal sacrificial material such as CD₄ - IR shield prevents infrared radiation from getting to capsule and slows hot gases getting to capsule - Capsule support membrane supports capsule against mechanical forces applied to the targets - Tracking fiducials compatible with tracking detection - Compatible with fusion chamber wall - Compatible with laser final optics (Mitigate damage, coating) - Compatible with hydrogen isotope separation (minimal H, no halides to corrupt Pd filters, minimal tritium gettering) - Minor activation to reduce high-level waste - Cost-effective recyclability 		Yes

Capsule production					
Production quantity				see plant reqs	No
Operation cost (COO)		Must meet cost objective for this operation - this cost includes labor, equipment cost, maintenance, consumables, utilities, factory overhead, inspection etc.		Total unfilled ablator cost shall be < \$0.01 each Total cost for fill and layer operations shall be <\$0.01 each	Yes
Dimensional tolerances				Capsules shall be manufactured per dwg	Yes
Material selection			Material selection must meet constraints imposed by other plant subsystems. These include: - Low-Z materials compatible with target physics requirements - Strong enough to survive manufacturing and injection mechanical forces - Thermal properties consistent with keeping DT cool - Properties consistent with layering techniques - Compatible with fusion chamber wall - Compatible with laser final optics (Mitigate damage, coating) - Compatible with hydrogen isotope separation (minimal H, no halides to corrupt Pd filters, minimal tritium gettering) - Minor activation to reduce high-level waste - Cost-effective recyclability		Yes
Assembly operations					
Production quantity				see plant reqs	No
Operation cost (COO)		must meet cost objective for this operation - this cost includes labor, equipment cost, maintenance, consumables, utilities, factory overhead etc.		Total cost of assembly operations shall be < \$0.01 each	Yes
Dimensional tolerances				Targets shall be manufactured per dwg	Yes
Material selection					Yes

5. OPERATIONAL SCENARIOS

A sequence diagram for the fusion fuel factory is shown in Figure 6. The factory in normal mode simply produces targets and sends them to the plant injector so that they may be injected into the fusion chamber. The production is largely “just in time” due to both the enormous number of fusion fuel targets which are consumed per day (~1 million per day) and because the plant tritium levels must be kept as low as possible for safety and plant licensing purposes. In the case where there is an error situation in the factory, for example, where non-conformal parts are being produced, reserve parts must be used while repairs are being made until there are no more parts in reserve. At this point the plant must go into shutdown mode until the repairs are complete.

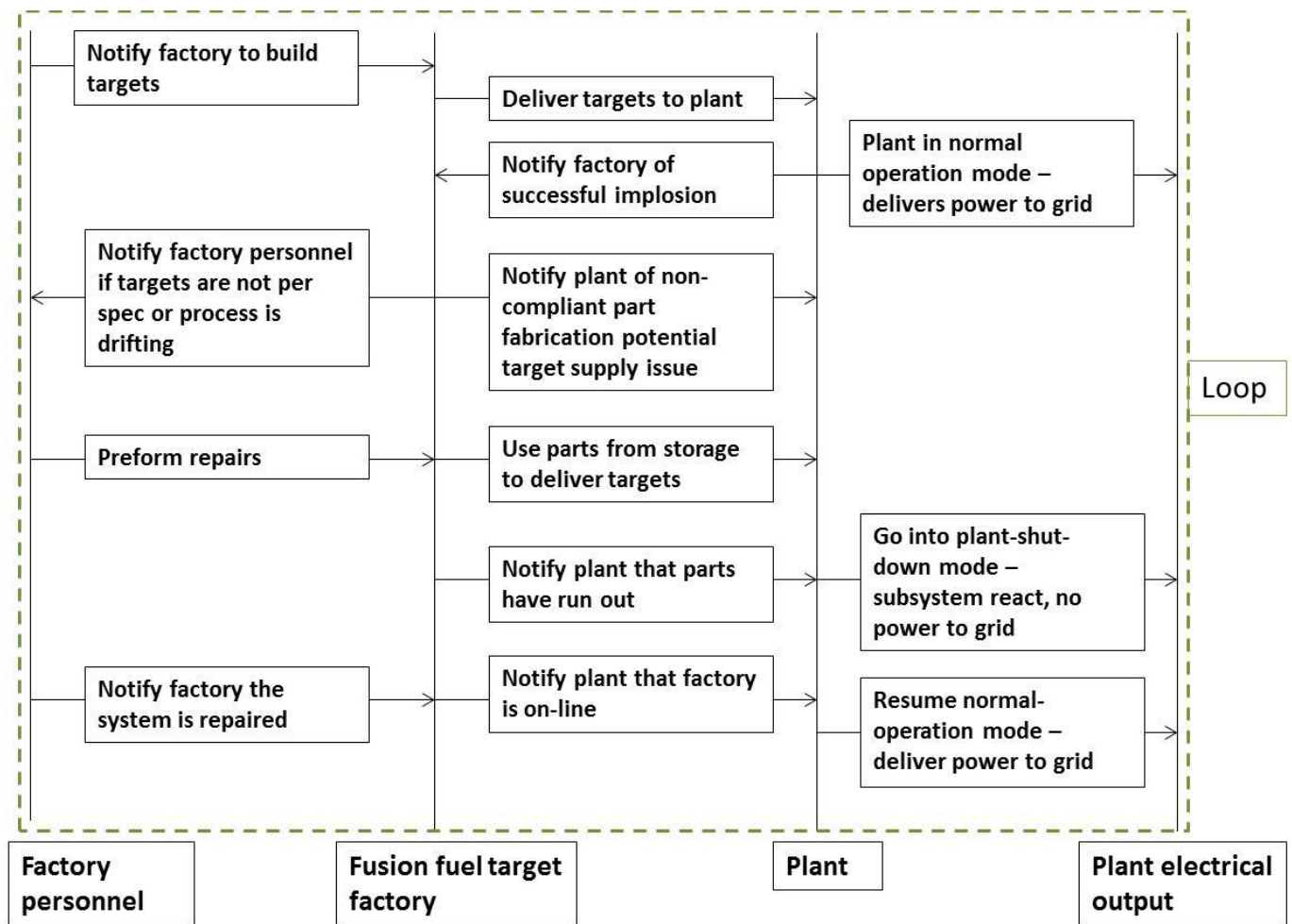


Figure 6. Sequence diagram for fusion fuel factory

6. IMPLEMENTATION CONCEPTS AND RATIONAL

A review of the various component material and process options is shown in Table 3. The credible material options are listed along with one or more process option for that material type. The option is rated against the major requirements for volume throughput, cost and precision requirements as well as

the requirement to deliver a system in a timely manner. As noted earlier, the material must also be compatible with the other sub-systems. The options are rated with a value of 1 to 5 against each requirement and the overall average score is tabulated. The best option for each sub-component is noted in the last column with a star.

Table 3. Fusion fuel target component material and process trade-off study matrix

Subsystem or element	Material options	Sub operations	Process options	Meets cost objectives	Meets throughput objectives	Meets functional/precision objectives	Can be delivered within 5 years	Is compatible with other subsystems	Average value
Capsule									
Mandrel	Silicon		Etch	5	3	5	5	5	4.6
	Silicon nitride		Etch	5	5	5	5	5	5
CVD diamond coating			Microwave plasma	2	3	5	3	5	3.6
			Hot filament	3	5	4	3	4	3.8
Foam	DCPD	Dispense	Vacuum fill	5	5	5	3	5	4.6
			Pipette	5	3	5	3	5	4.2
		Spin coat	2 axis spinner	1	2	3	2	5	2.6
			Single axis spinner	2	2	4	3	5	3.2
		Polymerize		5	5	5	5	5	5
		CO2 extraction		5	5	5	5	5	5
Hohlraum									
	Lead								
			Molding	5	5	5	5	2	4.4
			Pressing	5	5	5	5	2	4.4
			Sintering	5	5	5	5	2	4.4
	Xenon								
			Molding	5	5	5	5	5	5
			Pressing	5	5	5	5	5	5
			Sintering	5	5	5	5	5	5
Tracking fiducials			Press	5	5	2	5	5	4.4
	Reflective ink		Paint (stamp)	3	5	5	5	2	4
Joining material	Polymer adhesives		Paint (Stamp)	3	5	4	5	3	4
			Diffusion bond	5	5	5	5	5	5

Membranes										
LEH window	Polyimide		Spin-on	1	2	5	5	4	3.4	
			Meniscus coater	5	5	5	5	4	4.8	*
			Co-extrusion	3	5	5	5	4	4.4	
Sacrificial layer	Methane - deuterated		Paint	3	4	5	5	4	4.2	
	Pentane - deuterated		Paint	3	4	5	5	4	4.2	
			Degradation of base membrane material	5	5	3	5	5	4.6	*
IR shield	Polyimide		Spin-on	1	2	5	5	4	3.4	
			Meniscus coater	5	5	5	5	4	4.8	*
			Co-extrusion	3	5	5	5	4	4.4	
IR reflector	Aluminum		Sputter coat	4	5	5	5	2	4.2	*
P2 shield	Lead									
			Molding	5	5	5	5	2	4.4	
			Pressing	5	5	5	5	2	4.4	
			Sintering	5	5	5	5	2	4.4	
	Xenon									
			Molding	5	5	5	5	5	5	*
			Pressing	5	5	5	5	5	5	
			Sintering	5	5	5	5	5	5	
Assembly			Flexible tooling	3	3	5	5	5	4.2	
			Fixed tooling	5	5	5	5	5	5	*

7. PROPOSED SYSTEM ACRITECTURE

Table 4 shows the revised baseline based on the comparisons of the materials and processes to the requirements. The modified assembly diagram is shown in Figure 7. A few materials were changed. The pressed lead of the high Z hohlraum and P2 shield were replaced with molded xenon because of the large impact of lead on other plant sub-systems, notably the final optics (lead dust on the optics is bad) and the possible tritium retention in lead oxide could increase the overall tritium level in the plant to unreasonable levels. The other changes are to replace the silicon mandrel with a cheaper, more readily available silicon nitride mandrel and to change the microwave plasma diamond CVD deposition technique for the capsule with the readily expandable hot-filament technique. These changes are pending technical issues which may arise during the process development phase of the project.

Table 4. Revised fusion fuel target system

Component	Material	Sub operations	Process
Capsule			
Mandrel	Silicon nitride		Etch
CVD diamond coating			Hot filament
Foam	DCPD	Dispense	Vacuum fill
		Spin coat	Single axis spinner
		Polymerize	
		CO2 extraction	
Hohlraum	Xenon		Mold
Tracking fiducials			Press
Joining material	Polymer adhesives		Paint (Stamp)
Membranes			
LEH window	Polyimide		Meniscus coater
Sacrificial layer	Methane - deuterated		Droplet dispense
IR shield	Polyimide		Meniscus coater
IR reflector	Aluminum		Sputter coat
P2 shield	Xenon		Mold
Capsule support membrane	CNT-epoxy		TBD
Assembly	Polymer adhesive		Fixed tooling

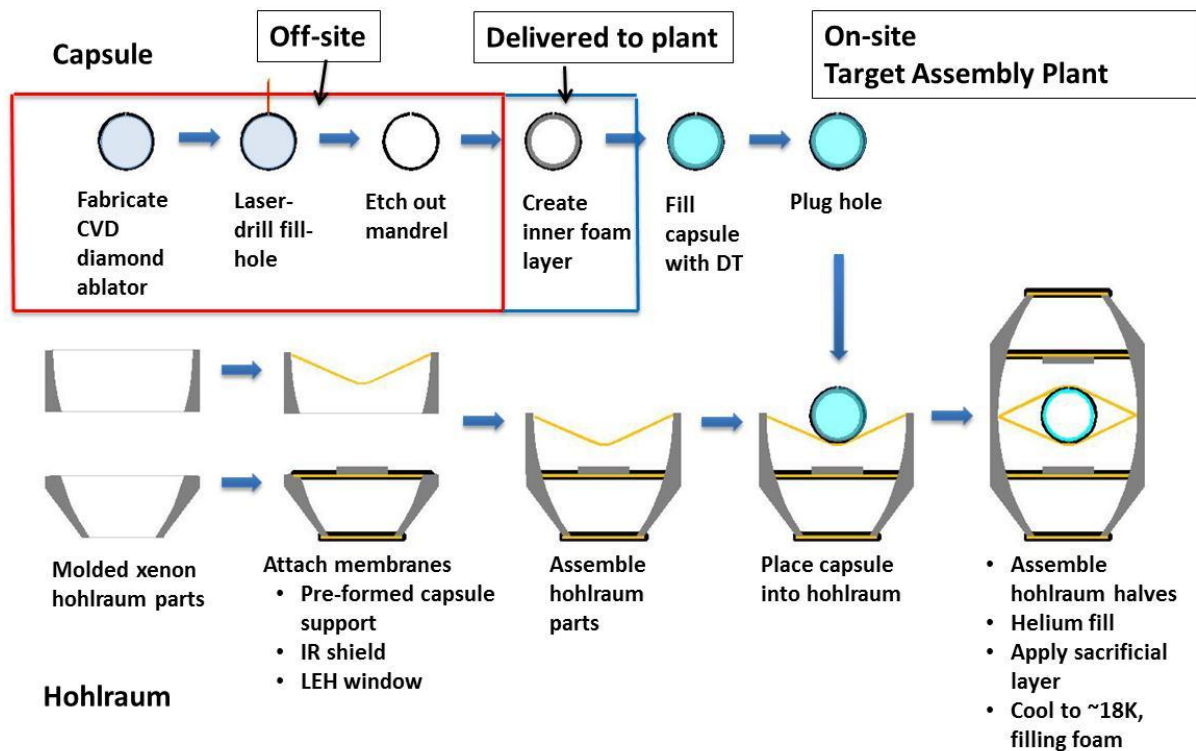


Figure 7. Modified fusion fuel assembly schematic

8. ORGANIZATIONAL AND BUSINESS IMPACT

Pending unforeseen technical issues, the proposed changes reduce the risk of achieving the overall plant cost and schedule objectives.

9. RISKS AND TECHNOLOGY ASSESSMENT

Table 5 shows the various risk factors associated with critical target components. The source of the risk to date is that current high-precision scientific targets are not fabricated using normal high-volume low cost methods. New fabrication methods will have to be honed to a state-of-the art level of precision within the relatively short period of time (~7 years) allocated in the overall plant build schedule. While it is quite likely for the overall process to be successful, the overall schedule risk is high.

Table 5. Risk factors for fusion fuel target production

Risk	Impact			Mitigation
	Description	Severity	Likelihood	
CVD too expensive for ablator	CVD diamond is generally an expensive process - it is expected that the cost can be decreased by a combination of increasing the batch size and the growth rate	High costs here require lower costs elsewhere. A costly target results in an uncompetitive cost of electricity	Medium-high	1. Two methods of CVD deposition can be pursued simultaneously (MWCVD and hot filament CVD) 2. Alternative ablator materials can be pursued (GDP, AI) 3. Cost can be compensated for in other processes
DT layering requires long, manual process	Current layering process is long ; averaging about 60 hours. The long process will increase target costs and increase tritium inventory to possibly unacceptable levels	Costly targets will make the plant uncompetitive. Too much tritium increases the safety risk.	Medium-high	Several approaches to fast -DT layering are being pursued
The capsule-support membrane	The requirements for the thickness of the capsule support membrane may be too stringent to permit high quality ignition (very thin membrane) or injection survivability (thick membrane)	Either condition, poor ignition or poor target survival will jeopardize the proper functioning of the plant	Medium	1. More laser power to get through thicker membrane 2. Possible alternative support configurations like threads (could be expensive)
Xenon hohlraum allows too much IR to pass through	If IR radiation or heat in general get to the DT layer then the implosion quality may not be acceptable	Poor ignition will defeat the proper functioning of the plant	Medium	1. A thin IR shield could possibly be applied to the xenon hohlraum 2. Careful analysis of the IR flux through the DT layer may result in a non-issue due to low IR absorption
Xenon hohlraum not mechanically robust	A fragile hohlraum may break and jeopardize the implosion process	Poor ignition will defeat the proper functioning of the plant	Medium	1. A higher strength hohlraum core could be used to increase strength 2. A different hohlraum material could be used which may result in other plant problems

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